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THE DEVELOPMENT OF EXTRA-HIGH-VOLTAGE SYSTEMS IN THE SOVIET UNION

Eng.B.P.Lebedev
Eng.S.S.Rokotyan
Prof.I.A.Siromyatnikov

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SUMMARY

I. Quite satisfactory results were obtained for the first period of operation of the two-circuit 400 kV Kuibishev-Moscow transmission system. The power transmitted over the line was raised to I200-I300 MW. The Kuibishev-Urals transmission line was put into service in I958. The length of 400 kV line erected as of January I, I959 amounted to 28I4 km.

2. It has been found possible to select the insulation level for the lines and sub-station equipment on the basis of an internal overvoltage value limited to 2,5 V phase. In connection with this the decision was taken to convert the 400 kV lines now in operation and under construction for a rated voltage of 500 kV, and to design new long-distance transmission systems (with a load of 750 MW per circuit and higher) at 500 kV. This voltage level will increase the transmitting capacity of the network and reduce the capital expenditures as well as the operation cost. The voltage 330 kV has been adopted for smaller capacity transmission systems.

3. Large development of extra-high-voltage transmission systems is planned for in the Soviet Union. According to the seven year plan(I959-I965) following work has to be done in this field: construction of 7800 km of 500 kV line and 7000 km of 330 kV line , consolidation of the largest power systems of the European part of the Soviet Union and creation of consolidated power systems in the Caucasus, in Middle Asia and in Central Siberia.

4. Great research work on extra-long-distance (2000-3000 km) and large transmitting capacity (2000-3000 MW) systems at 650-750 kV a.c. and at ±600 to ± 700 kV d.c. is being carried out in the Soviet Union.

INTRODUCTION

Rapid growth of the Soviet national economy, in which the rate of development of the electric power industry is stressed, necessitates the intensive development of large power systems and networks of large transmission capacities. As power systems grow they become interconnected in accordance with the development plan for economic zones in which they are located; afterwards power systems in neighbouring economic zones will be interconnected, such as those in the European part of the Soviet Union, in the Caucasus, in Middle Asia in Central Siberia, etc. These power-pool systems servicing vast areas will be created in the course of the seven year period from I959 to I965 according to the approved plan.

A large number of complex technical and economical problems arise in connection with the transmission of large blocks of power or transport of fuel over long distances.

When long-distance power transmission turns out to be more economical than transporting fuel following additional advantages can be obtained that must be taken into account when designing the interconnected power system.

a) Inter-system ties are provided, which reduce the total load peak and the reserve capacity required; moreover, thermal and hydraulic resources are more economically exploited;

b) Power stations and networks along the route of the transmission line may be connected to the latter and form a consolidated power system, thereby improving the reliability of these systems. This permits to build large more economical power stations of 1000 MW and higher capacity with big units (of 100 to 300 MW rating).

c) New areas are electrified.

When determining whether or not it is expedient to develop extra-high-voltage networks, the expenditure for erecting local networks for distributing the power transmitted over the extra-high-voltage lines must be taken into account. In several cases the cost of such networks may be greater than the cost of networks for power stations constructed in the receiving system. A rotating reserve must be provided for the case of an emergency tripping of the extra-high-voltage line during load peaks. The cost of the rotating reserve required to ptevent disconnection of consumers must be taken into account when making an economical comparison of alternative schemes.

Work carried out in the Soviet Union showed that the posibility of using single-phase automatic reclosing for 400-500kV lines which enables us to reduce the rotating reserve capacity in the receiving system. It is necessary to use high and extra-high-voltages for the conditions of the Soviet Union with its vast territory. When interconnecting power systems that are comparatively near to each other, the voltage 330 kV and sometimes 220 kV is used.

The voltage 500 kV has been selected for the consolidated power system of the European part of the Soviet Union, for Siberia, for Middle Asia and elsewheres. This voltage will also be used at the outstart in creating the Consolidated Power System for the entire Soviet Union; in the future a higher voltage of 600 to 750 kV will be required for this purpose.

Our first 400 kV transmission system- the Kuibishev-Moscow line, has been described in the literature (see Ref. 1-9) and therefore we will only mention its basic characteristics in this paper.

The 400 kV Kuibishev-Moscow Transmission Line

Construction work on the 400 kV Kuibishev-Moscow line was started in 1952. The first stage of the transmission , two parallel circuits 815 and 890 km long on single-circuit towers, with three switching stations and two receiving sub-stations in the Moscow area, were put into service in 1956. In 1958 two additional 400 kV sub-stations and the series-capacitor installation were put into service.

The 400 kV receiving sub-stations in the Moscow area have similar schemes, and have two banks of 400/110/11 kV, 270 MVA each of single-phase transformers and two banks of 220/110/11 kV, 180 MVA transformers. The intermediate sub-stations have 400/220/11 kV, 405 MVA autotransformer banks.

The series capacitor installation is located at the second switching station, which is approximately in the middle of the line. It consists of three parallel circuits having a total rating capacity of 486 MVAR, a rated current of 2250 A and an impedance of 32 ohms per phase. These series capacitors compensate 25% of the line reactance. They are installed on metal platforms, which are insulated to ground by suspension strings of porcelain insulators.

The power transmitted to Moscow over two circuits in 1958 reached 1200 MW.

From the date the line was put into regular service on May 1, 1956, till January 1, 1959 more than 16 billion kwh were delivered over the line to Moscow.

The transmission system is equipped with the necessary equipment for regulating voltage and reactive power flow. In addition to the possibility of changing the voltage on the 400 kV bus-bars of the step-up substation by means of the generators at the hydro-electric station, the transmission system is equipped with shunt reactors (5 banks of 50 MVA each), synchronous condensers (4 condensers of 75 MVA at each receiving substation in the Moscow area) andan under load tap-changing device in the power transformers (within ± 12.5%) at the receiving and intermediate sub-stations. Operating experience has confirmed the necessity of using the above listed means of regulation.

During trial operation period of the transmission system and in the course of its first stage of commercial operation, many different tests were conducted to determine the parameters of the line and equipment; to measure the corona losses , the radio and telephone interferences, the internal overvoltage levels; to check the relaying and automatic reclosing devices; tests were made for self-synchronizing the water-wheel generators at the Volga hydroelectric station.

In 1957 tests were made for evaluating the steady-state stability limit of the transmission system. The transfer capacity limit of one circuit of line 815 km long working in a block scheme when the water-wheel generators were equipped with ordinary excitation regulators and no series capacitor compensation was connected amounted to 570 MW. In 1958 testes were conducted to determine the transfer capacity of the Kuibishev-Moscow line when the water-wheel generators were equipped with automatic "strong action" excitation regulators. The transfer capacity limit of one circuit of line 815 km long at a voltage of 420 kV amounted to 720 MW with the series-capacitor installation disconnected.

The insulation of the line and equipment in the 400 kV transmission system was designed in accordance with following principles:

The neutrals of the 400 kV power transformers are solidly grounded;

the 400 kV transmission line is protected along its entire route against direct lighting strokes by two ground wires with a protective angle of 20°;

the tower footing resistance under normal soil conditions does not exceed 10 ohms;

the sub-stations are protected against direct lighting strokes by surge-diverters;

autovalve lighting arrestors are installed at the substations.

The industrial frequency (50c/s) test voltage level was determined assuming a 3 times phase voltage value of internal overvoltage across the main insulation. The 50 c/s wet flash-over test voltage was taken to be 700 kV r.m.s. for the substation equipment and 775 kV r.m.s. for the line insulation.

The full-wave 1.5/40 microsecond impulse voltage has a peak value of 1500 kV for the substations equipment, 1900 kV between the disconnecting switch contacts and 1800-2000 kV for the line insulation.

Series of tests were carried out for studying internal overvoltages in the 400 kV system. Overvoltages were studied when disconnecting a 400 kV transformer at no-load as well as a shunt reactor , and also when switching various sections of the line in and off, as well as when clearing short circuits on the 400 kV line.

The following are the maximum voltages measured when testing the line without the series capacitor installation: across the main insulation - 2.4 Vphase; between the breaker contacts - 2.6 Vphase.

Large overvoltages were observed only under extremely unfavorable conditions which were not provided for the normal working scheme of the transmission system.

In schemes with series capacitor compensation the overvoltages were naturally higher. Their value was limited by arrestors, shunting the battery of capacitors. This enables the overvoltage across the main insulation to be held down to about 3 Vphase. Across the circuit breaker contacts these overvoltages attained values up to 3.4 $V_p$hase.

Despite the numerous lightning storms along the line route, in 1956 and 1957 there was no case of line faults on this account. In 1958 the Kuibishev-Moscow line was tripped twice due to lightning faults. None of the other 400 kV lines put into operation in 1957-1958 have been tripped due to lightning. Thus the specific fault occurance due to lightning of 400 kV transmission lines in the USSR is 0.042 per 100 kilometer-years.

Increasing the Voltage of 400 kV Transmission Lines in Service

The experience gained in designing the Volga Hydrostation-Moscow transmission system as well as the Volga Hydrostation-Urals and Stalingrad Hydro-station_Moscow systems indicates that costly measures have to be taken to ensure the stability of the 400 kV line when transmitting 500 to 800 MW per circuit over a distance of about 1000 km and greater.

This fact urged us to make a carefull analysis of the expediency of employing a higher voltage 500 kV. A comparison of the technical and economic characteristics for a transmission system transferring 700-800 MW per circuit over distances of 800 to 1000 km showed that the voltage 500 kV would reduce capital expenditure by 5 to 10% and operation costs of power transmission by 8 to 13%.

When using the voltage 500 kV we may do away with series capacitor compensation and thereby reduce the internal overvoltages value.

The following factors were also taken into consideration when solving this problem:

the overvoltages actually measured on the transmission line Volga Hydrostation-Moscow without series capacitor compensation;

the development of the extra-high-voltage network and the presence of intermediate substations and ties with local systems; this reduces the internal overvoltage level;

the progress achieved at present in circuit breaker design, which enables to reduce the overvoltages during switching by using shunt resistors and to eliminate breakers arc-back.

the possibility of limiting the value of overvoltages by installing special arrestors, which were developed at our research Institutes.

As a result it was decided that we had all the grounds to select the insulation level for 400-500 kV transmission systems on the basis of an internal overvoltages level of 2.5 Vphase instead of 3 Vphase, which was originally adopted for 400 kV networks.

Since the internal overvoltage level was reduced, it was found possible to transfer the existing 400 kV lines to a voltage of 500 kV and to use the 400 kV sub-stations equipment at 500 kV after some minor alternations.

Considering that it is technically and economically expedient to increase the transmitting capacity of lines when the extra-high-voltage network and the capacity transferred over it is in the process of rapid growth, the decision was taken to convert the 400 kV networks being erected and in service in the Soviet Union for a rated voltage of 500 kV, and to design all new long-distance transmission systems, and in particular the Siberian ones, for 500 kV from the outstart.

Fig.I gives a diagram for the Kuibishev-Moscow and Stalingrad-Moscow transmission systems when connected for operation at 500 kV.

Further Development of Extra-High-Voltage Lines in the USSR

After the erection of the 400 kV Kuibishev-Moscow transmission line, construction work got under way in I957 on the extra-high-voltage Stalingrad-Moscow and Kuibishev-Urals lines as well as on several other lines in the Urals.

In I958 construction work was started on 500 kV lines in Siberia; in I959 on the ± 400 kV Stalingrad-Moscow d.c. transmission line, and the first link in the Ural transmission network from Kuibishev to Zlatoust (76I km long) was put into service.

In the European part of the Soviet Union as of I959 there are 28I4 km of line and 9 sub-stations at 400 kV in service.

The first 500 kV line, one circuit of the Stalingrad-Moscow transmission, will be put into service in I959.

By I965, during the second stage in creating the extra-high-voltage systems, another 7800 km of line and 25 step-up and step-down sub-stations at 500 kV will be constructed. The voltage 330 kV will be used in some areas of the Soviet Union and during the coming seven-year period about 7000 km of line and over 50 sub-stations at 330 kV will be constructed. Construction work on the first lines of this voltage was started in I958.

Fig.2 gives a diagram for extra-high-voltage networks in the European part of the Soviet Union as of I965. It was compiled on the basis of data from design bureaus.

Technical Problems for Power Transmission at Extra-High-Voltages

A. The Scheme of the Transmission System

Since there were no clearly held concepts on the effectiveness of several measures for improving the steady-state and transient stability of the transmission system, it was decided to use all of the measures known at the time for increasing the transmitting capacity of the line when designing the first 400 kV transmission system so as to gain experience; these are:

I) The use of bundle conductors;

2) The use of series-capacitor compensation;

3) The reduction of the reactances of power transformers and water-wheel generators;

4) The use of switching sub-stations sectionalizing the line into four parts;

5) Special design of excitation regulators for the water-wheel generators at the Volga hydro-electric station having a higher ceiling and a faster rate-of-rise of the excitation voltage;

6) The installation of "strong action" excitation regulators used in the synchronous condensers at the receiving sub-stations as well as in the generators;

7) The use of high-speed relays and circuit breakers clearing faults in the 400 kV network within 0.I2 seconds;

8) The use of electrical and mechanical devices for braking the water-wheel generators.

Analysis of test results and operating experience have shown that reducing the reactance and increasing the inertia constant for the water-wheel generators is not justified economically.

Whether or not it is expedient to use mechanical and electrical devices for braking the water-wheel generators will be determined after tests will have been made.

Automatic "strong action" excitation regulators have shown themselves to be very effective. They enable the voltage to be held constant not only at the generators, but also on the 400 kV side.

Shunt reactors are installed to keep the voltage within required limits, to reduce line losses and to lower internal overvoltages. Some of these reactors must be connected on the high-voltage side (at 400-500 kV), while others may be connected on the secondary voltage buses at the intermediate substations (at 35 or II0 kV).

The connection scheme, the layout and the design of the switchgear at the 400-500 kV switching sub-stations make it possible to develop the latter in the future into II0 or 220 kV receiving sub-stations for supplying the adjacent area with electric power.

B. Transmission Lines

The transmitting capacity of one circuit of 500 kV line should be not less than 500-750 MW. With the economic current density of ACSR conductors equal to 0.5-0.6 A/mm^2, the cross section of the aluminum current-conducting part of the conductor should be at least I200-I600 mm^2 per phase.

Bundle conductors are used so as to retain standard cross sections of the conductors, as well as to reduce the line reactance, the corona losses and radio interference. Three conductors in a bundle located at the apexes of an equilateral triangle which are 400 mm away from each other is the design practice in the Soviet Union.

Special specifications are in force in the Soviet Union for 400-500 kV lines, which are somewhat more stringent as to mechanical strength requirements when compared with the design code for II0 and 220 kV lines. Special attention is given to ensuring their reliability during strong winds and sleet conditions.Reduction of the design loads for the suspension towers was an important measure in obtaining an economical design for the 500 kV lines, since these towers comprise 90% of all towers used.

For this purpose releasing clamps or clamps with a limited holding capacity may be used. In any case, the force applied to the suspension tower should not exceed I.5 to 2.0 tons in the event of rupture of the three conductors of the phase. Thus the tower design is determined by normal operation conditions when all the conductors are intact. Releasing clamps of special construction were used in the first 400 kV lines in the USSR. They were designed for a three-conductor phase bundle. These clamps were tested at the test-stand and now have a good performance on the Kuibishev-Moscow line. The disadvantage of releasing clamps is the necessity of having to use strain towers (usually angle-strain towers) every 7-I0 km to limit the line section in which the wire may fall to the ground when all three conductors of a phase bundle break.

In order to do without strain towers, clamps with limited holding capacity are now used instead of releasing clamps Here, the conductors upon breaking slide in the clamps thereby limiting the forces applied to the suspension tower and limiting the faulty line section. At present clamps of this type have passed tests successfully and are used in the new 500 kV lines being constructed.

In the first 400 kV lines H-frame suspension towers (fig.3) were used with pillars, solidly anchored to their foundations and hinged to the cross-arm. The distance between adjacent phases is I0.5 meters; the height to the insulator suspension point is 27 meters. The tower weighs from 7.3 tons (for geed weather areas) to 8.6 tons (for areas with strong winds).

Suspension tower foundations for all new lines under construction permit work to be carried out throughout the year. These foundations are either pre-fabricated reinforced concrete mushroom shaped footings (8 footings 1.16 m^3 each) or reinforced concrete piles (8 piles 0.3 by 0.3 by 7.0 meters per tower).

In many 500 kV lines suspension towers with guy wires are used with their pillars hinged to their foundations. These towers save metal, (their weight is 7.2 tons for strong wind areas) and simplify the design of the foundations (its volume is reduced from 8 ÷ 9 m^3 to 3 m^3 per tower). It was found possible to use ordinary hard fixing clamps on these towers since the deviation of the suspension point in the case of a phase rupture permits the force applied to the tower to be reduced to a safe value.

Towers for lines from 220 to 500 kV have been designed using centrifugal pre-stressed reinforced concrete pipes. At present several factories are being built that will manufacture these towers.

Strain-angle towers for 400-500 kV lines with tension insulator strings are of the bar type for all lines under construction. Very severe requirements are imposed on the design of these towers, for they must be capable of operating as dead-end towers and also of taking on the load when two phases (6 conductors) covered with sleet are broken.

In the 500 kV lines that do not use strain towers with tension strings, H-frame angle towers have been designed for turn angle up to 20°, with the conductors held in suspension strings.

330 kV lines are designed with a single conductor per phase and also with a two-conductor phase bundle. Tests have shown that the 330 kV transmission lines with the single-conductor phase may be more widely used than it was expected until now. A design for single-circuit H-frame towers with guy wires has been worked out that is similar to the 500 kV towers described above. These towers weigh to 7 ton and they are designed for a two-conductor phase bundle (type ASO-480 is to be used). A distance of 8.2 meters between phases has been adopted.

A two-circuit tower has also been designed with the phases arranged in a "barrel" scheme with two ground wires. The height of this tower is about 40 meters. It is designed to carry two conductors per phase of ACO-330 type. The vertical distance between the cross-arms is 6 meters, and the phases are spaced 2 meters from each other along the horizontal. This tower weighs about 7 tons.

C. 400 - 500 kV Substations

Economical and at the same time reliable triangular and square connection schemes are employed for the receiving substations. The "transformer-busbar" arrangement has been selected as the connection scheme for the substations in the Moscow ring of the Volga Hydro-station-Moscow transmission system.

The 400-500 kV receiving substations located near large load centers step the power right down to 110 kV. These sub-stations usually have two transformer or autotransformer banks of 270 MVA each (fig.4).

For less concentrated loads and also when the substation is to be used as a reversible one the voltage is stepped down to 220 kV and one or two autotransformer banks of 405 MVA each are installed there.

The 500 kV bay is 28 meters wide, the line bay is 161 meters long and the distance between phases is 6 meters. A phase bus is made of two hollow copper conductors of 300 mm^2 cross section located in the horizontal plane 400 mm away from each other.

The equipment for 330 - 500 kV substation is manufactured by the electrical industry of the USSR.

Transmission Systems of Higher Voltages

The voltage 400 kV has been put into service in the Soviet Union and almost three years of operating experience has been gained. Development of 500 kV is the task for the immediate future. As it was already mentioned, the first transmission system at this voltage will be put into operation in 1959.

The voltage 500 kV permits 750 to 1000 MW to be transmitted over 1000-1200 kilometers per single circuit of line.

The growth of the national economy of the Soviet Union, the task of creating a consolidated power system to service all the territory of our country, the exploitation of rich hydraulic and coal resources of Siberia sets forth a problem that must be solved in the not too far off future, the problem of creating more powerful and longer transmission systems than the 500 kV lines that would be capable of transferring 2000 to 3000 MW per circuit over 2000 to 3000 kilometers. Transmission systems of such a large scale can be made either by using alternating current at 650 to 750 kV or by using direct current at ± 600 to ± 750 kV. Great research and design work in this field is being carried out in the Soviet Union. An important stage on the way to developing powerful transmission systems is to collect construction and operation experience from the 500 kV lines as well as from the 400 kV, 750 MW, 500 km Stalingrad-Donbas d.c. transmission system.

Research work in the field of long-distance a.c. transmission at 650-750 kV is being carried out at test installations to determine the dielectric strength of large air gaps, investigation of corona losses, stability and transmitting capacity of the system, the insulation level, the magnitude of internal overvoltages and other problems. Work on developing new designs for transmission lines and high-voltage equipment is also being carried out.

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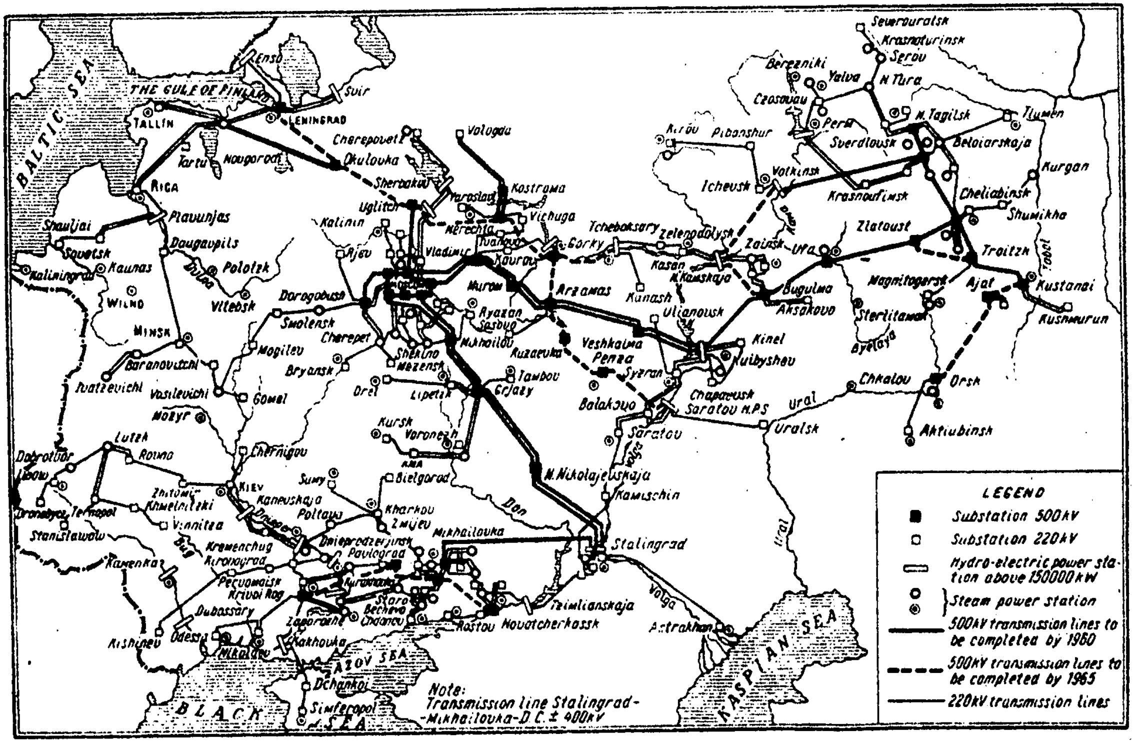

Fig. 2. — Diagram of 500 kV systems in the European part of the Soviet Union for 1960 and 1965 (plan).

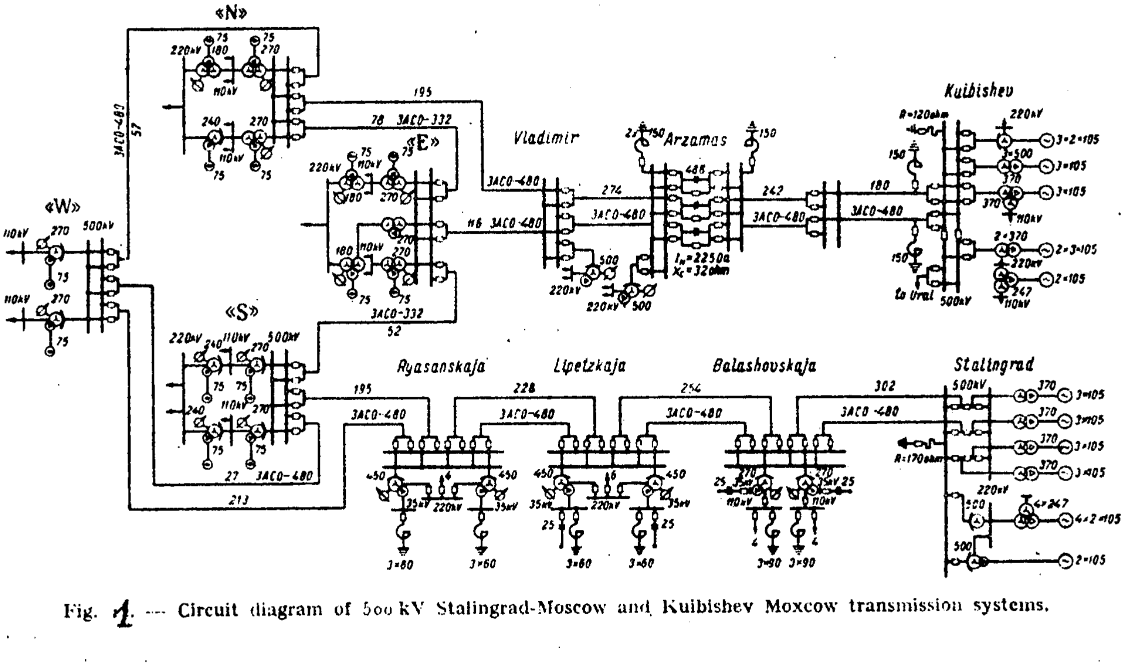

Fig. 1. — Circuit diagram of 500 kV Stalingrad-Moscow and Kuibishev Moxcow transmission systems.

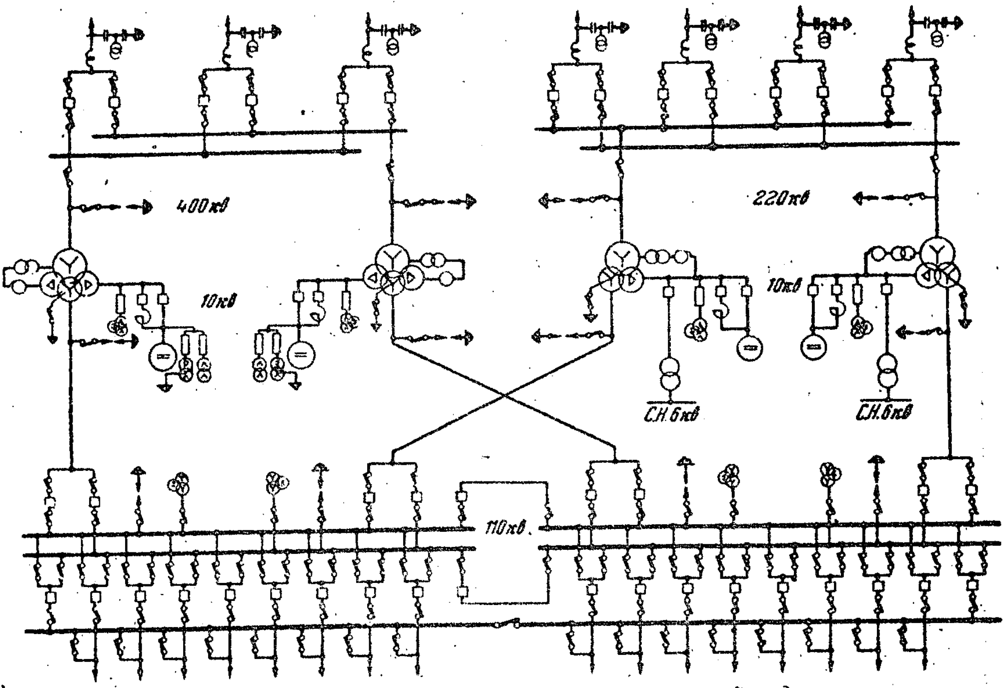

Рис. 4. Схема электрических соединений понизительной подстанции.

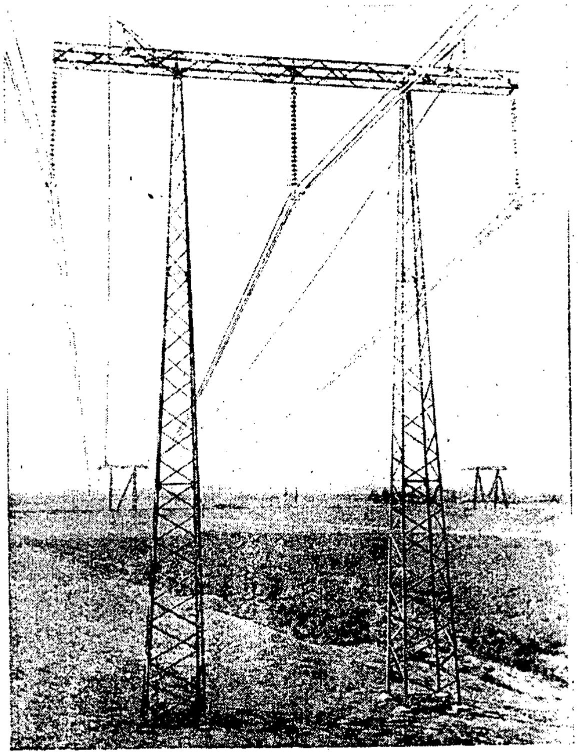

Рис. 3. Внешний вид промежуточной опоры.